EXPERIMENTAL ANALYSIS OF CURVED LAMINATED GLASS BEAM

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TEVFİK UZHAN

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EXPERIMENTAL ANALYSIS OF CURVED LAMINATED GLASS BEAM

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ABSTRACT

EXPERIMENTAL ANALYSIS OF

CURVED LAMINATED GLASS BEAM

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In this thesis, experimental studies are carried out on curved laminated glass beams to form a database for the scientists who may like to test their mathematical models. Beams which are only free to rotate and constrained in radial direction at both ends are tested to make the data available for further calculations. Test setup is prepared to minimize error that could occur due to test setup and data readings. Material testing machine and 4 channel data collecting machine are used to measure the signals at the strain gauges located over the glass beam. Within the range of force applied to the specimens, laminated curved beam shows linear behavior without any fracture. Data collected from the specimens are in conformance with each other. Results obtained from experiments are compared with the results obtained from the mathematical model developed by Aşık and Dural (2006). As it is observed from the

graphs presented, experimental results from the tests and numerical results from the mathematical model are in good agreement.

Keywords: curved laminated glass, glass beams, laminated glass, laminated glass beams, large deflection, bending, membrane

ÖZ

KAVİSLİ LAMİNA CAM KİRİŞLERİN

DENEYSEL ANALİZİ

Uzhan, Tevfik

Yüksek Lisans, Mühendislik Bilimleri Bölümü

Tez Yöneticisi: Prof. Dr. M. Zülfü Aşık

Mayıs 2010, 33 Sayfa

Bu tezde, kavisli lamina cam kirişler üzerinde deneysel çalışmalar yürütülerek matematiksel modeller geliştiren bilim insanları için bir veritabanı oluşturulmuştur. İki ucu da dönebilen ve radyal yönde sınırlandırılmış kirişler test edilerek daha ileri hesaplamalar yapılabilmesi için veriler kullanıma sunulmuştur. Test düzeneği ve okunan verilerde oluşabilecek hatayı minimize edecek şekilde test düzeneği hazırlanmıştır. Malzeme test cihazı ve 4 kanallı veri toplama cihazı kullanılarak cam üzerindeki gerinim ölçerlerden gelen sinyaller ölçülmüştür. Lamina kavisli kirişler testlerde uygulanan kuvvet sınırları içinde kırılmaksızın doğrusal davranış göstermektedir. Numunelerden toplanan veriler birbirleriyle uyum içerisindedirler. Testlerden elde edilen değerler Aşık ve Dural (2006) tarafından oluşturulan matematiksel modelden elde edilen değerler ile karşılaştırıldı. Sunulan grafiklerden gözlendiği gibi deneylerden elde edilen sonuçlar ve matematiksel modeldeden elde edilen sonuçlar uyum içerisindedir.

Anahtar sözcükler: kavisli cam kiriş, cam kirişler, lamina cam, lamina cam kirişler, büyük yerdeğiştirme, eğilme, zar

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I am very proud and thankful to have a chance to study with Prof. Dr. M. Zülfü Aşık. His problem solving skills, positive attitude, guidance and contribution to the study, made it possible to finalize this thesis. Experiments and their difficulties was overcome with the enermous effort and experience of Assist. Prof. Dr. Mehmet Yetmez who sometimes even with a telephone call helped us to solve a lot besides his presence in the labarotory for alongated periods. I would like to thank to Ebru Önlü Dural for her support in experiments and her knowledge. Dora Glass and her friendly staff provided full support throughout this process by supplying glass specimens on time, volunteerly.

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CHAPTER 1

INTRODUCTION

1.1 Laminated Glass

1.1.1 Application Areas

Laminated glass is mainly used in automotive industry and for construction purposes. Due to the Polyvinil Butyral (PVB) after a force that could fracture the glass, no sharp-edged pieces will be formed to cause injury to human beings nearby. This functionality forced designers to use laminated glass wherever there may be an injury risk around.

Being separated with PVB, forms a barrier for the ultraviolet (UV) radiation to penetrate. Apart from the UV barrier, laminated glass is functional as it also dampens noise.

All these important functional purposes and the architectural properties that are not mentioned above makes laminated glass favorable.

Nowadays there are several companies supplying laminated glass according to the demand. The production of laminated glass is important as this process increases the value of glass. This is important for Turkey as being one of the biggest glass producer country with several industrial plants dedicated for glass production, employing many workers.

1.1.2 Mechanics of Curved Laminated Glass

Laminated glass comprises two layers of glass and a layer of viscoelastic polymer PVB film. Two layers of glass and PVB in between is put together under heat and pressure. Interlayer improves mechanical properties of the laminated glass. First of all it increases the area of impact which increases the impact resistance as a result. As stated before, interlayer in between keeps together broken pieces that can possibly cause dangerous incidents or accidents. The laminated glass as a system dampens the energy of impact improving the brittle structure when compared with monolithic glass structure.

Curved structure compared with a straight beam also has certain advantages on the application where the direction of expected resistance is determined. Specially as an automobile glass, curved beam resists forces coming from outside. Manufacturers of laminated glass for automobiles apply routine tests on their products to determine if an insider force applied can easily break the laminated glass to prevent injuries on cases where passengers inside a car can recover from accidents that may occur because of cuts that laminated glass could be responsible for.

PVB mainly determines the mechanical characteristic of laminated glass beams on varying temperatures. Transition temperature of PVB is effective on the mechanical properties. Over transition temperature PVB tends to become viscous. Laminated glass structure in this case tends to act as layered structure. Under transition temperatures PVB is tending to become brittle. Laminated glass structure then tends to act as a monolithic structure becoming more brittle.

PVB’s important role on the structures behavior makes it interesting to conduct studies on its content. Plasticizer content determines the transition temperature of PVB. PVB tends to become more brittle upon decreasing the plasticizer content.

1.2 Previous Research

Studies on laminated glass beams were first conducted by Hooper (1973) to deal with the architectural properties rather than that of structural loading. Main importance of architectural glass is that it doesn’t collapse when it is fractured, and it has capability of shading and control of solar heat gain by the materials that could be applied in between two layers of glass. A mathematical model for the bending of laminated glass beams under four-point loading is based on a previous solution to a problem on the bending of parallel beams interconnected by cross members. In this approach, the solution method is centered on replacing the discrete assemblage of interconnecting cross-members by a continuous medium of equivalent stiffness, the medium itself being firmly attached to the beams at each interface. Hooper sees that this condition is related to architectural laminated glass, where a relatively soft continuous layer is present between two glass layers. Also these two layers remain in adhesive contact with PVB during bending. Differential equation is solved for one of the glass plies via Laplace transform, presenting factors proportional to the axial force in one of the plies, shear strain in the interlayer and central deflection. PVB is a viscoelastic material and its shear modulus approaches zero as time increases.

As a conclusion, Hooper remarks that sustained loads result in creep deformation within the plastic interlayer. Creep deformation is not present at relatively low temperatures. Creep deformation allows the glass layers to deflect as though they are interconnected at a constant distance by a material of equivalent shear modulus. Transient loads on laminated glass beams respond as composite or tend to respond as monolithic material with interlayer shear modulus varying with the temperature. For structural design, as it may contain sustained loads like snow, it is better to consider laminated glass beam as a layered unit. For transient loads like wind, laminated glass beam can be considered as a laminate on the basis of the expected highest temperature and the solar radiation effect to the layer in between.

Behr et al. (1985), conduct research on laminated glass specimens on various temperatures considering that the thickness of PVB interlayer is several orders of magnitude less than that of glass and conclude that the effect of the interlayer is likely proven to be not too large. Assuming that the effect of the PVB will be low, finite element solutions are determined for such a layered system. Numerical solution for the structure is provided as if it is having two adjacent plates without any interaction. Temperature effect is found to play an important role over the composite action of the laminated glass beam.

Experimental studies are conducted for different temperatures to determine the effect of the interlayer that may cause the structure to act like monolithic or layered glass.

Vallabhan et al. (1987) present and discuss strength factors for different load and aspect ratio conditions. Involving nonlinear theory of rectangular plates, variation of the strength factor is observed for different forces applied over glass plates.

Strength factor (SF) is defined as:

$$Strength\ factor = \frac{\text{Maximum principal tensile stress in monolithic glass plate}}{\text{Maximum principal tensile stress in layered glass plate}}$$

Vallabhan et al. (1987) use von Karaman theory to find a finite difference solution for monolithic and layered glass plates. For evaluation purposes resulting data are presented for different aspect ratios and with a dimensionless load. Aspect ratio is b/a where the area of a complete plate is 2a X 2b. These numerical solutions show that the force acting over the plates cause the strength factor to increase nonlinearly when the force exceeds the critical force. In Figure 1.1, the regions of pressure and area where SF is exceeded 1.0 on design charts for various aspect ratios are observed.

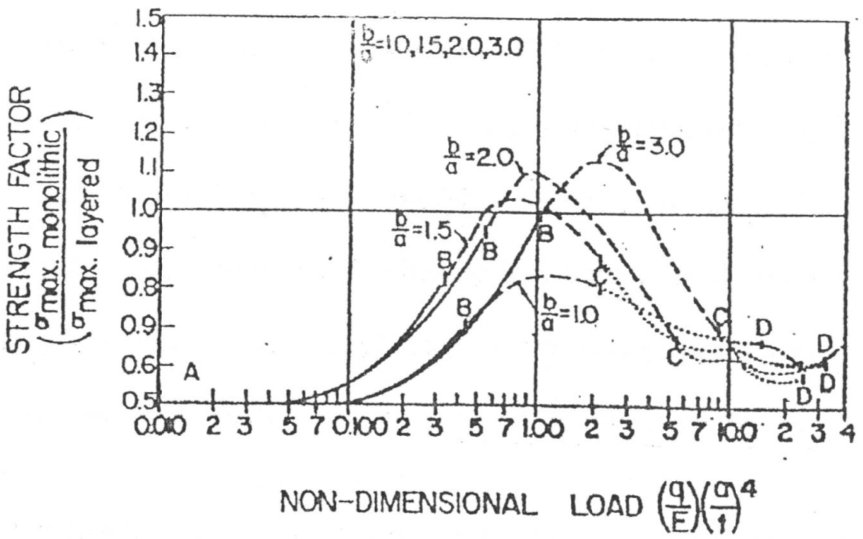


Figure 1.1. Variations in SF as a function of nondimensional load (Vallabhan 1987).

As shown in Figure 1.2, authors note that there are favorable conditions at which maximum tensile stress was smaller than that of monolithic glass, enabling comparison with monolithic glass plates.

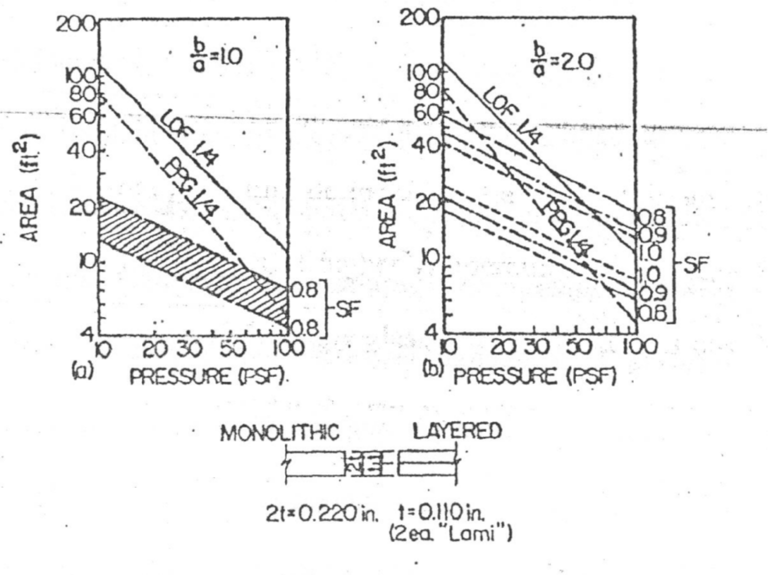


Figure 1.2. Comparison of SF with current window glass design charts (Vallabhan 1987)

Minor et al. (1990) conduct tests to compare their test results with model building codes by publishing strength factors between 0.6 and 0.75. After destructive and non-destructive tests Minor et al. conclude that there are cases such that, below 49°C there are laminated glasses that exceed those published values. Such cases are common where there are transient forces present, like wind loads.

Behr et al. (1993) perform experimental and theoretical studies on laminated glass beam to determine the structural properties and behavior. Apart from clearly explaining the properties that affect its behavior, Behr et al. mention environmental effects and the method of applying forces to the laminated glass specimens with different aspect ratios. Impact resistance is increasing with the thickness of PVB layer in between. There are two critical temperatures that form the basis for comparing the laminated glass beam with monolithic and layered plates. At temperatures 0°C and below, beams are showing similar features like monolithic glass beams as they react permanent forces like snow in the same fashion. Between 0°C and 49°C composite behavior is observed such as that, only for transient loads it behaves like monolithic. Over 49°C layered behavior is present.

Behr et al. (1993) note that temperature effects on the behavior of laminated glass structure is not significant at room temperatures. In their experiments, a severe degradation of effective shear modulus is observed in the interlayer only at 77° C. Among the reasons they propose to explain this difference, the difference of PVB chemistry is the most likely, given the similarity of the transition temperature they find with that of the hard interlayer in Hooper's experiments.

The results deduced by Behr et al. (1993) from these experiments are that laminated glass behave like monolithic glass at temperatures up to 49° C, after which degradation in shear modulus of the interlayer occurs and the glass begins to behave in the manner of a layered glass system, and that laminated glass behaves like a monolithic glass under long term loading and at temperatures at and below 0° C. This second result is another evidence that the interlayer used (Saflex PVB from Monsanto Chemical Company) resembles the hard rather than the soft interlayer in Hooper experiments. There it is the hard interlayer which displays no creep at 1.4° C, while the soft interlayer displays considerable creep.

But this fact implies that the results from the experiments of Behr et al. (1993), which yield a type factor of 1.0 for up to 49° C, may be true only for the specific PVB used in these experiments unless SF > 1.0 phenomenon is valid for the concerned geometry and loading. Therefore, it would be wrong to apply a strength factor of 1.0 in design without knowing the transition temperature of the specific PVB used in the laminated glass.

Mathematical method and numerical solution for laminated glass beams are presented by Vallabhan et al. (1993) for analyzing the bending behavior of laminated glass units. The total potential energy of plates is minimized by using variational methods. Their assumption is that; the plates are possessing both bending and membrane strain energies, but interlayer has only shear strain energy. Modeling of the glass plates has been done via von Karman nonlinear theory of the plates. Minimizing the total potential energy of the system with respect to five displacement parameters; namely, the individual in-plane displacements in x and y directions of the two plates and the common lateral displacement, five differential equations and their associated boundary conditions are derived. These are solved by using finite difference method with over-relaxation. Experiments are conducted with strain gauge measurements to verify the model. The relation between the results of the mathematical model and the experiments are found to be quite close.

Edel (1997) concludes that, for laminated glass beams it is better to use strength factor 0.75 and above for structural purposes to be on the safe side because risk for failure is critical at those applications and with temperature 25° C and above.

Norville et al. (1998) develop an engineering mechanics model which assumes that the interlayer performs solely the functions of maintaining spacing between the plies and transferring a fraction of the horizontal shear force between the glass plies. They express the horizontal shear force that the interlayer transfers between glass plies as the product of a shear force transfer parameter and the horizontal shear force transferred by the middle fiber of a glass only monolithic beam. When this parameter is zero, the laminated glass beam acts as a layered glass beam with symmetrical stress distributions in the individual plies. When it is 1.0 it behaves as a glass only monolithic beam, the stresses on the inner surfaces of the plies being zero. When the parameter is at its maximum value, which is unlikely because of the difference in moduli between glass and PVB, the stress distribution throughout the section is such that stress is zero at the middle fiber of the interlayer. From this point they proceed to relate the load-induced moment carried by the beam and the horizontal shear force transferred between the glass plies. By this relation an effective section modulus for the LG beam is derived. They verify this model with the results of the experiments by Behr et al. (1993), obtaining the shear force transfer parameters from the analysis of test results.

They also preform LG lite tests and observe that LG series displayed mean fracture strengths ranging from 98% to 230% that of monolithic series of the same dimensions.

Norville et al. (1998) conclude that "For most LG constructions the fraction of shear force transfer required to produce effective section moduli equivalent to or greater than monolithic glass of the same nominal thickness designation was less than l", and that even at 49° C laminated system stresses remained far below layered system stresses. From the results of Behr et. al. (1993) experiments, it is obvious that both the fraction of shear force required to produce effective section moduli equivalent to monolithic glass, and the upper bound for temperature at which laminated glass behavior emulates monolithic behavior rather than layered behavior, is dependent on the plasticizer content of the interlayer and therefore the transition temperature of the laminated glass. The figures presented in the study may display great variations for laminated glass with an interlayer with a transition temperature lower than 49° C. The same point is also valid for the relative breaking strength of LG lites.

Van Duser et al. (1999) develop a finite element model which incorporates a linear viscoelastic modeling of the PVB interlayer and a statistical model for glass breakage based on Weibull effective stress, based on the study by Bennison et al. (1999). Shear relaxation and bulk moduli of the Butacite interlayer are determined by measurements and a Maxwell fit is used to model the decrease of shear relaxation modulus with time. This model is combined with a statistical description for glass fracture. Another improvement in this model is the explicit inclusion of interlayer thickness, which increases the section modulus of laminated glass. Their model shows that Weibull effective stress, a statistical measure of probability of failure, is lower for laminates than for the equivalent monolithic glass plate under almost all conditions studied for the considered model. Another result is that the concept of layered and monolithic limits, based on small strain analysis of beams, could be highly misleading and on transition to membrane like behavior, the limits themselves collapse. Due to the increase in section modulus affected by interlayer thickness, the authors point out that laminates could be stronger than monolithic limit.

CHAPTER 2

MATHEMATICAL MODEL

Aşık (2004) develop mathematical method for behavior of laminated circular glass plates. Numerical solutions are expressing nonlinear behavior under high pressure values when the effective membrane stresses develop.

Aşık (2004) carry out analysis on strength factor and temperature effect on laminated glass beams. Behavior of laminated glass beam is affected by temperature since the shear modulus of PVB interlayer exhibits great changes with respect to temperature, increasing with falling temperature and decreasing with rising temperature due to plasticizer content of PVB.

Aşık et al. (2006) develop equations for the laminated glass arch shown in Figure 2.1 by using variational and minimum potential energy principles and end up with coupled differential equations. “It is assumed that glasses have bending and membrane resistances”. As it is a soft material PVB layer is assumed to have shear resistance only. Total potential energy is then written as the following:

$$\Pi = U_m^1 + U_b^1 + U_m^2 + U_b^2 + U_I + V \tag{1}$$

Where $U_m^{1,2}$ and $U_b^{1,2}$ are the membrane and the bending strain energies for the outer and inner glass arch, respectively; U_I is the shear strain energy in the interlayer, and V is the potential energy function due to the applied loads.” Here, Π is written in terms of the radial displacement w and circumferential displacements u_1 and u_2 as follows:

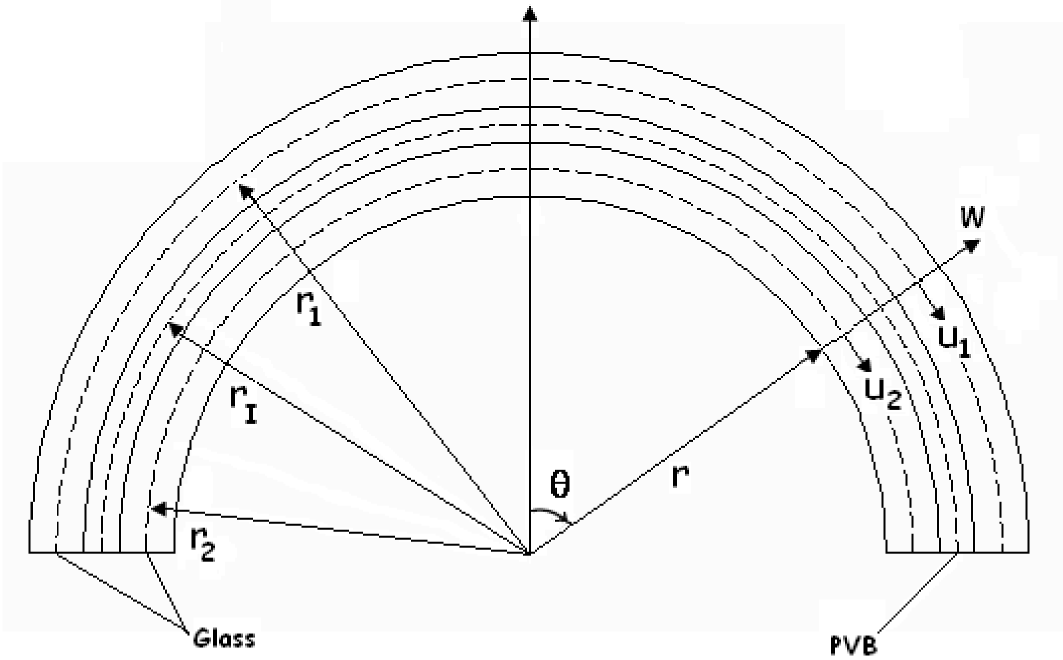


Figure 2.1 Laminated glass arch.

$$\Pi = \sum_{i=1}^{2}\left\{\int_V \tfrac{1}{2}E(\varepsilon_m^i)^2 dV + \int_V \tfrac{1}{2}E(\varepsilon_b^i)^2 dV\right\} + \int_V \tfrac{1}{2}G(\gamma_I)^2 dV - \int_0^s qwds \tag{2}$$

where

$$\varepsilon_m^1 = \frac{1}{r_1}\left(\frac{du_1}{d\theta} + w\right) + \frac{1}{2}\left(\frac{w_\theta}{r_1}\right)^2 \tag{3}$$

$$\varepsilon_m^2 = \frac{1}{r_2}\left(\frac{du_2}{d\theta} + w\right) + \frac{1}{2}\left(\frac{w_\theta}{r_2}\right)^2 \tag{4}$$

$$\varepsilon_b^1 = -z\frac{w_{\theta\theta}}{r_1^2} \tag{5}$$

$$\varepsilon_b^2 = -z\frac{w_{\theta\theta}}{r_2^2} \tag{6}$$

$$\gamma_I = \frac{u_1 - u_2 - \left(\frac{1}{r_1}\frac{h_1}{2} + \frac{1}{r_2}\frac{h_2}{2} + \frac{t}{r_I}\right)\frac{dw}{d\theta}}{t} \tag{7}$$

In figure 2.1 laminated glass arch is shown where this figure also describes the notation.

Solutions are obtained by using finite difference method and successive over relaxation (SOR) method to solve the matrix obtained from finite difference method. SOR is an iterative method to solve linear set of equations. SOR converges faster than Gauss Seidel method. Numerical results of these differential equations are compared with our experimental results. These differential equations are:

$$\frac{d}{d\theta^2}\left(EI\frac{d^2w}{d\theta^2}\right) - \frac{d}{d\theta}\left(\left(\frac{N1}{r_1} + \frac{N2}{r_2}\right)\frac{dw}{d\theta}\right) + \left(N1 + N2\right) + Gbr_I\left(\frac{1}{r_1}\frac{h_1}{2} + \frac{1}{r_2}\frac{h_2}{2} + \frac{t}{r_I}\right)\frac{d\gamma_I}{d\theta} = qr_1 \tag{8}$$

$$\frac{dN1}{d\theta} - Gb\gamma_I = 0 \qquad (9)$$

$$\frac{dN2}{d\theta} + Gb\gamma_I = 0 \qquad (10)$$

where N1 and N2 are the outer and inner circumferential forces in glass arches, respectively. γ_I is the shear strain in the interlayer; G is the shear modulus of interlayer; E is the modulus of elasticity of glass; h_1 and h_2 are the thicknesses of outer and inner glass arches; b is the width of the unit; q is a uniformly distributed load; I is the moment of inertia of the glass arches. Boundary conditions for the problem are w=0, u_1=0, u_2= 0 at the ends of the unit.

Aşık et al. (2008) investigate the effect of support conditions on the behavior of laminated glass plates. "Simply supported and fixed boundary conditions are considered. To derive the governing differential equations, minimum potential energy and variational principles are employed. Nonlinear system is solved by SOR procedure. In simply supported unit, maximum tensile stresses occur at corners as tensile stresses. For fixed support boundary conditions, it is different; maximum stresses occur at first at the center of plate as tensile stress, then symmetrically move along the x and y-axis as tensile stress, at last, for higher loads, settle as compression stresses where x and y axes are intersecting with the edge of the plate."

In this thesis, for each experimental value, these equations are solved to compare all the data and to verify mathematical modeling.

CHAPTER 3

EXPERIMENTAL SOLUTION

3.1 Test Specimens

7 test specimens that are supplied by Dora Glass with glass thickness 5+5 mm and PVB thickness of 1.52 are used for the tests. A representative specimen is presented in Figure 3.1 and its geometric and material properties are given in Table 3.1.

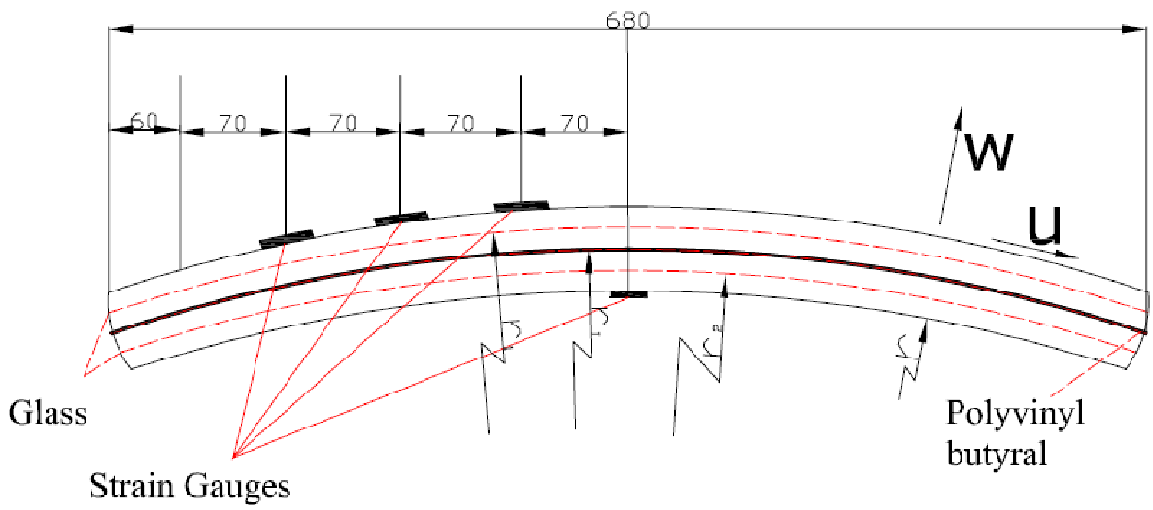


Figure 3.1. Laminated glass beam (Dimensions in mm).

In Figure 3.2 strain gauge positions on test specimens are shown.

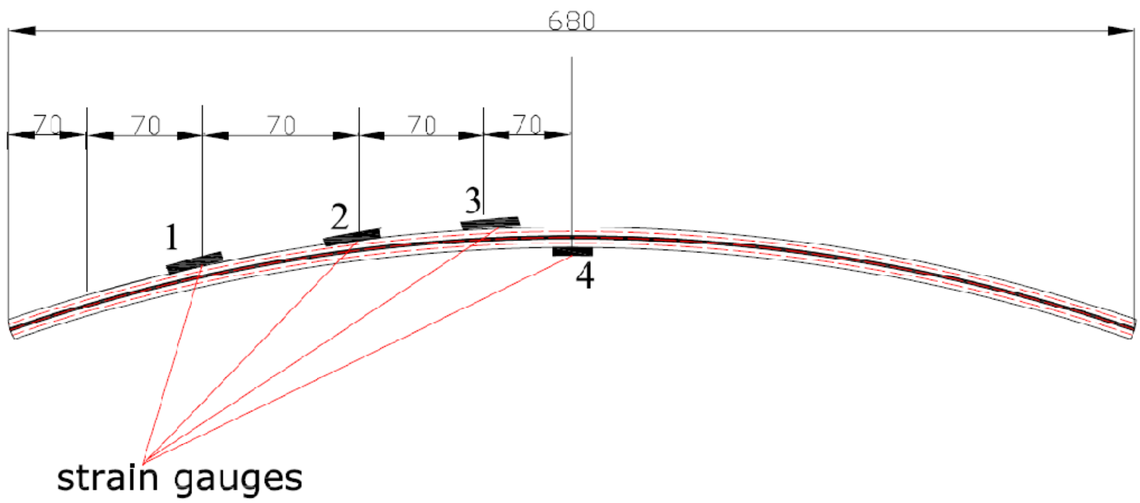


Figure 3.2. Strain gauge illustration and naming on laminated glass beam (Dimensions in mm).

Table 3.1 Physical properties of laminated glass beam

	Dimensions (mm)					Modulus	
	Thickness	Length	Width	Arch Length	Radius	E	G
Glass1	h_1=5	680	b=10	700	r_1=1000	70 GPa	26.2 GPa
Glass2	h_2=5	680	b=10	700	r_2=1000	70 GPa	26.2 GPa
PVB	h_I=1.52	680	b=10	700	r_I=1000	4.92 MPa	1.64 MPa

In figure 3.3 as seen below a photograph of the specimens is presented.

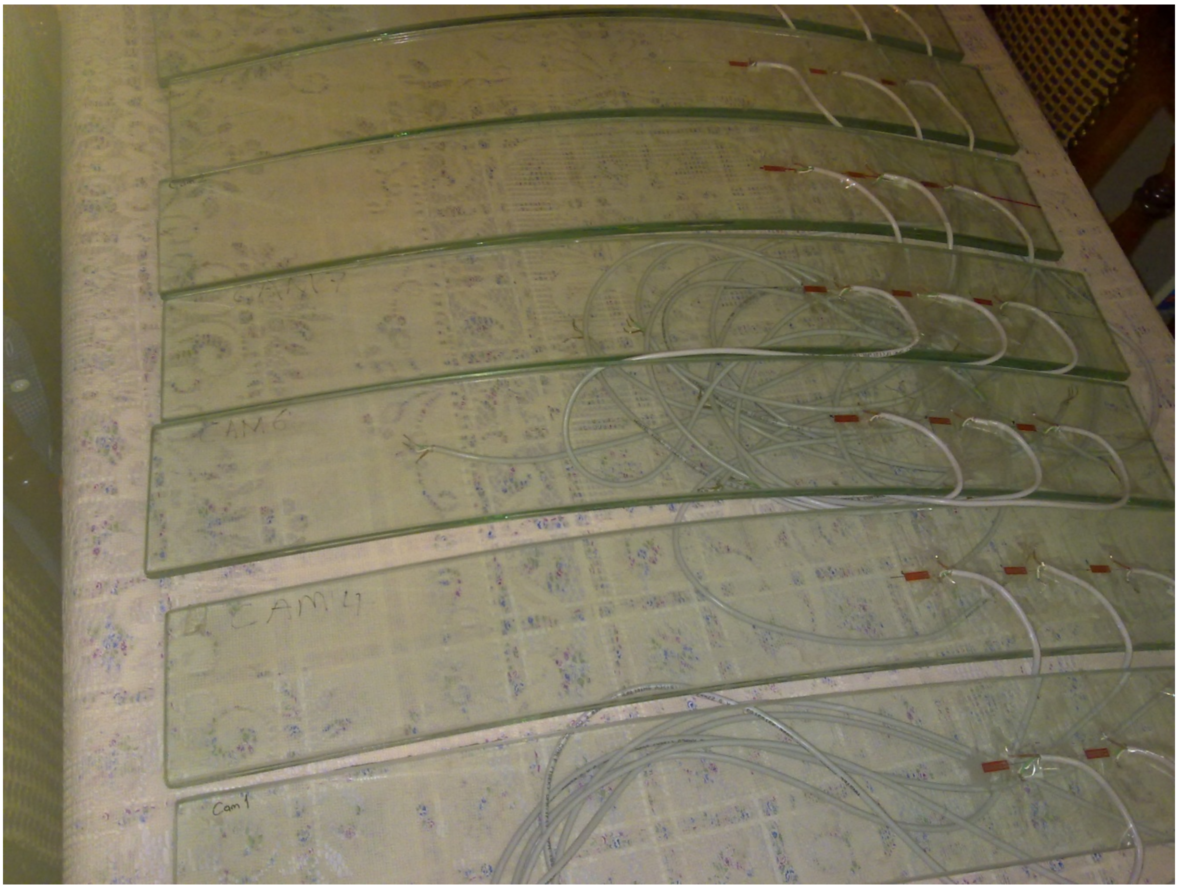


Figure 3.3. Curved laminated glass specimens.

3.2 Test Setup

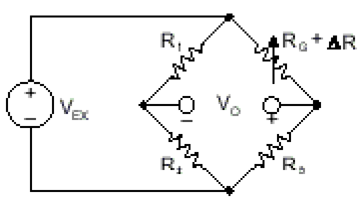
In Figure 3.4 the apparatus and setup used to conduct tests for the simply supported beam conditions are presented. Lloyd Inst. Ltd. LR50K material testing machine and NEXYGEN software are used for testing the specimens. 4 channel strain gauge indicator is used to collect data from strain gauges. Maximum effort is spent on the test setup to check the dimensional alignment and balance relatively between testing machine and test specimen, to reach good quality data.

Figure 3.4. 3-point bending setup for laminated glass beam.

3.3 Testing Procedure

Different forces are applied to the specimens for different setup conditions. After reaching the target value for the force, after 1 minute data are collected from strain gauges and from the material testing machine. Due to the nature of the simply supported beam setup, 6 cm. from both sides are left free and span length is decreased from 700 mm. to 580 mm. At each setup condition, speed of the material testing machine is 5 mm/min. This is enough for us to reach the target quality. Strain gauges with 120 Ohm and 10 mm length are used. Temperature of the laboratory is about 22-23° C, and humidity is about 25-28 %. The target force is 500 N.

From the www.davidson.com.au web site following is the details about quarter bridge "Since the invention of the electrical resistance strain gauge more than a half century ago, the Wheatstone bridge has become the sensing circuit of choice in most commercially available strain gauge instrumentation. This popularity is due in large measure to its inherent ability to 1) detect the small resistance changes produced in the strain gauge when it follows even minute dimensional changes on the surface of a test part under load, 2) produce a zero output voltage when the test part is at rest, and 3) provide for compensation of temperature-induced resistance changes in the strain gauge circuit. To varying degrees, each of these factors is essential for accurate strain gauge measurements. In the majority of strain gauge applications for the determination of the state of stress on a test-part surface, individual strain gauge elements, whether from uniaxial or rosette strain gauge configurations, are connected independently to the Wheatstone bridge in a quarter-bridge arrangement. In figure 3.5 quarter bridge formulation is presented showing the relation where strain ε is calculated. For our case gauge factor is taken to be 2.099 as declared by the manufacturer of the strain gauges.



$$\frac{V_O}{V_{EX}} = -\frac{GF \bullet \varepsilon}{4}\left(\frac{1}{1 + GF \bullet \frac{\varepsilon}{2}}\right)$$

Figure 3.5 Quarter bridge formulation.

The wiring scheme chosen to connect the strain gauge to the bridge circuit has a significant effect on the accuracy of measured strain data.

In particular, use of a two-wire connection is generally not recommended because it may introduce a significant resistance offset in the strain gauge circuit; temperature changes in the leadwire system will introduce errors into measured strain data; and the leadwire system will reduce the sensitivity of the strain gauge circuit. Configuring the strain gauge input as a three-wire circuit provides for intrinsic "bridge balance" and automatic compensation for the effects of leadwire temperature changes on measured strain data, and reduces the loss in sensitivity present in the two-wire configuration. Consequently, the three-wire connection is the recommended hookup for quarter-bridge strain gauge circuits for static strain measurement.” Therefore, it is decided to use three wire quarter bridge arrangement to measure the strain values.

3.4 Results

In Table 3.1 values that are obtained from the data logger and material testing machine for the readings of simply supported setup are presented. In Table 3.2, again for the simply supported setup, readings from data logger and from material testing machine are presented at three other positions of strain gauges, which are strain gauges 1, 2 and 3. Strain gauges are located at 13 cm from the edge and 7 cm away from each other along the half of the specimen. The last strain gauge is at the bottom face and center of the beam, which is in tension when the force is applied.

Table 3.2 Central deflection and central maximum stress comparison for experimental and mathematical model results.

	Central Deflection (mm)			Maximum Stress(MPa)		
Load (N)	Exp.	Model	Std. Dev.	Exp.	Model	Std. Dev.
0	0.00	0.00	0.00	0.00	0.00	0.00
50	1.72	1.21	0.44	7.37	7.27	0.04
100	2.80	2.43	0.32	14.84	14.55	0.31
150	3.88	3.64	0.29	22.17	21.82	0.20
200	4.96	4.86	0.31	29.45	29.11	0.36
250	6.04	6.07	0.32	36.33	36.39	0.99
300	7.12	7.29	0.32	44.03	43.68	0.62
350	8.19	8.51	0.24	50.33	50.97	1.92
400	9.27	9.73	0.28	59.80	58.27	0.89
450	10.35	10.95	0.29	66.62	65.56	1.03
500	11.43	12.17	0.41	73.90	72.87	0.95

Table 3.3 Maximum stress comparison for experimental and mathematical model results at strain gauges 1, 2 and 3.

	Maximum Stress(MPa) Gauge 1			Maximum Stress(MPa) Gauge 2			Maximum Stress(MPa) Gauge 3		
Load (N)	Exp.	Model	Std. Dev.	Exp.	Model	Std. Dev.	Exp.	Model	Std. Dev.
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	1.14	1.41	0.18	2.87	2.54	0.12	4.64	3.96	0.32
100	2.36	2.82	0.28	5.79	5.09	0.21	9.36	7.92	0.39
150	3.55	4.23	0.47	8.70	7.64	0.41	14.07	11.88	0.69
200	4.71	5.64	0.64	11.62	10.19	0.49	17.69	15.85	2.15
250	5.95	7.06	0.81	14.58	12.74	0.65	23.54	19.81	1.07
300	7.12	8.47	0.91	17.48	15.29	0.69	28.21	23.78	1.13
350	8.33	9.89	1.09	20.42	17.85	0.88	33.46	27.76	1.48
400	9.54	11.30	1.33	23.43	20.41	1.06	37.85	31.74	1.80
450	10.76	12.72	1.47	26.46	22.97	1.11	42.77	35.71	1.84
500	11.97	14.14	1.68	29.45	25.53	1.30	47.62	39.70	2.13

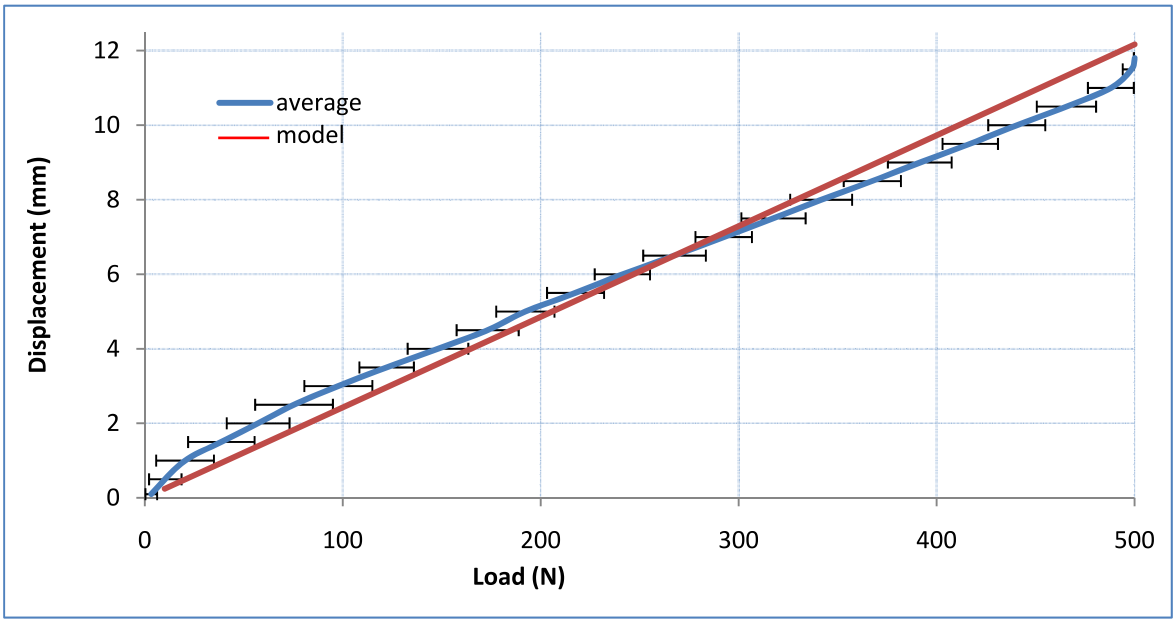


Figure 3.6. Simply supported beam readings at the center from the material testing machine and numerical solution

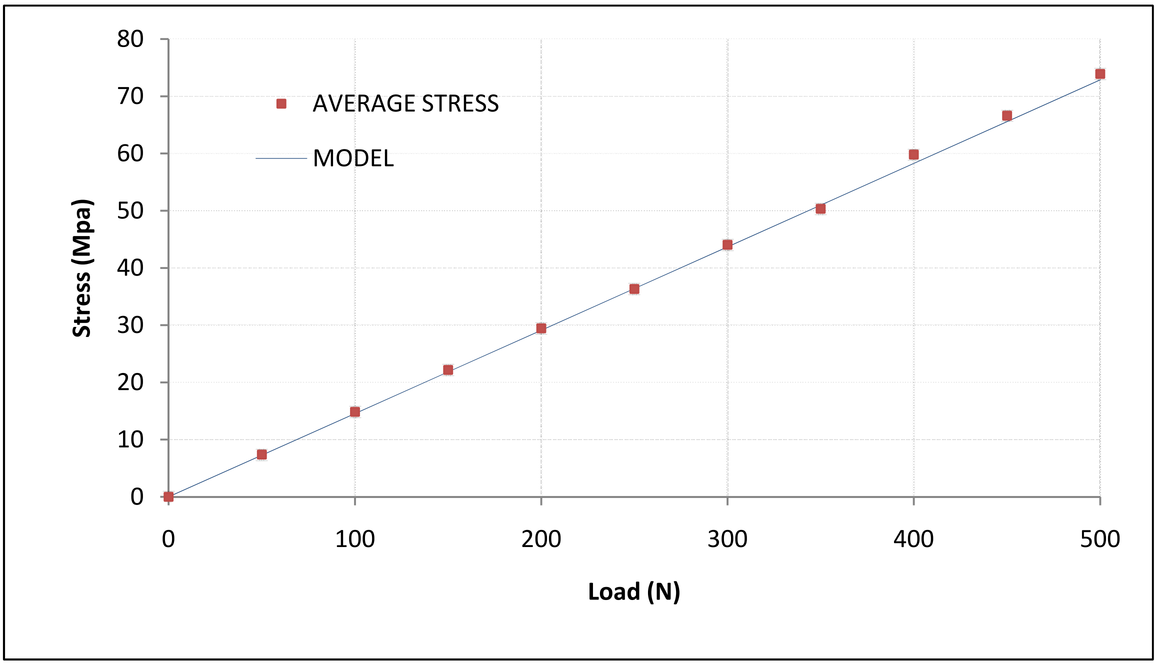


Figure 3.7. Stress-load relation for simply supported beam readings from the strain gauge 4 and numerical solution

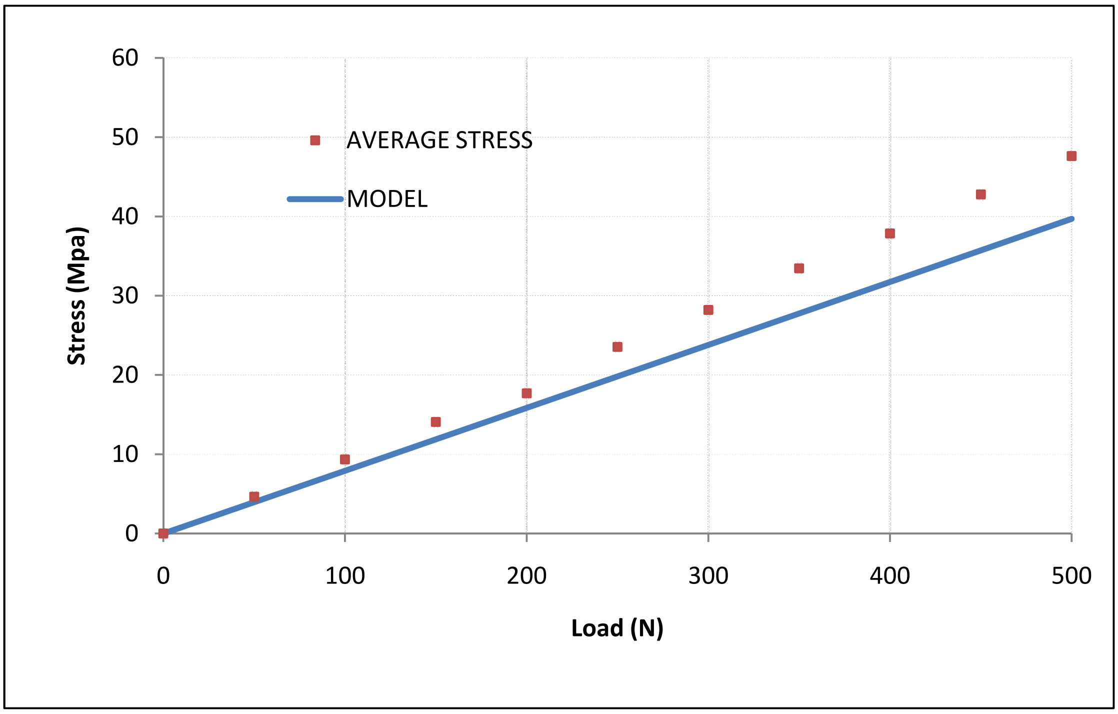


Figure 3.8. Stress-load relation for simply supported beam readings from the strain gauge 3 and numerical solution

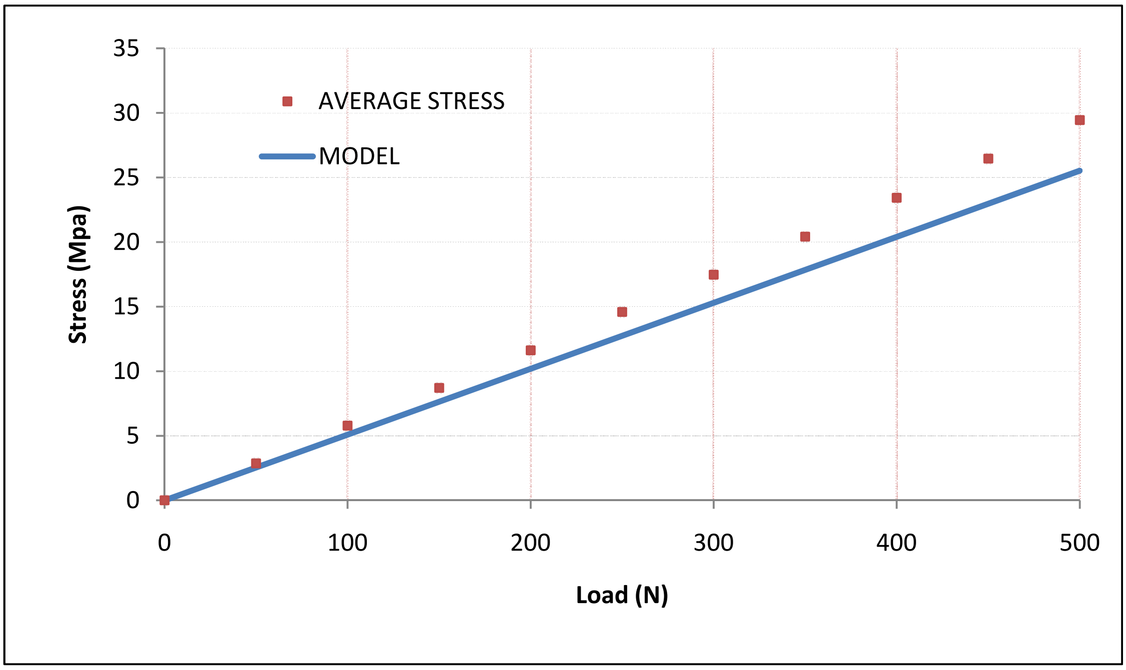


Figure 3.9. Stress-load relation for simply supported beam readings from the strain gauge 2 and numerical solution

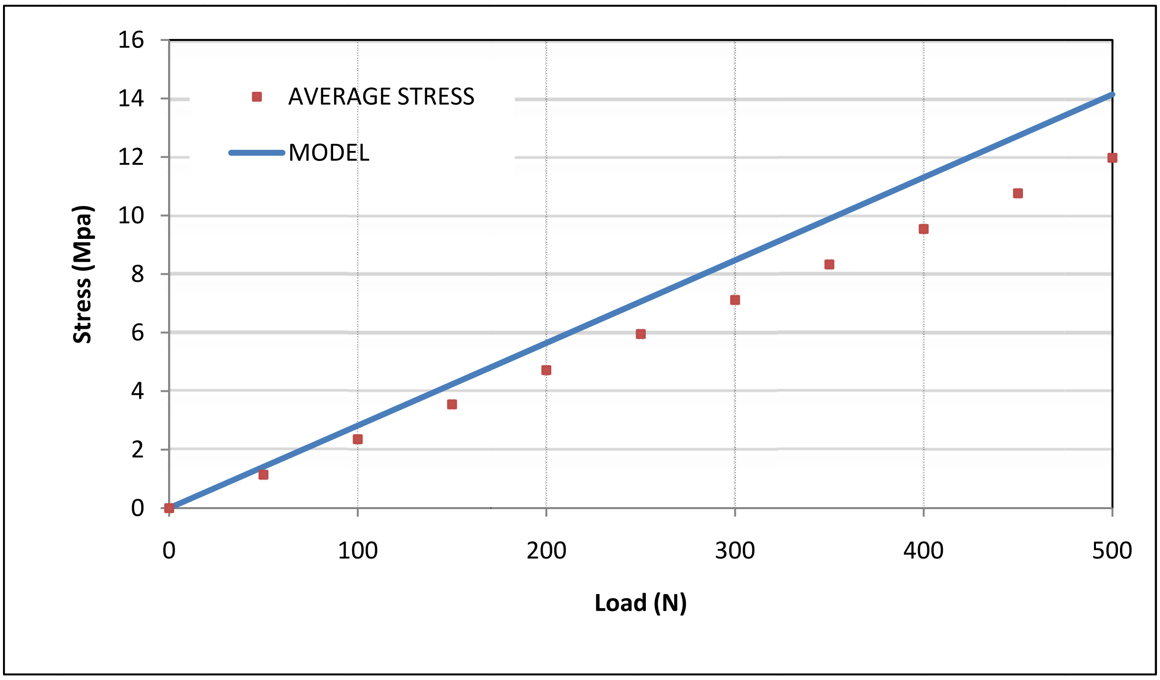


Figure 3.10. Stress-load relation for simply supported beam readings from the strain gauge 1 and numerical solution

CHAPTER 4

CONCLUSION AND SUGGESTIONS

From the figures 3.7, 3.8, 3.9 and 3.10, it is clear that the mathematical model proposed by Aşık et. al (2006) is in accordance with our test results. The mathematical model is successfully representing the behavior of the laminated glass arch. Within the range of force that tests are conducted, test specimens are within the elastic limit giving us the possibility to repeat tests by using the same test specimens. Data supplied from the tests are enough to make a comparison with the mathematical model.

Speed and duration of the force can be named as transient load like the wind. These conditions are not likely to be considered as permanent loads. Standard deviation is increasing as we collect data with increasing load. This may be due to decreasing amount of strain or displacement. Experimental results and mathematical model is almost same at the center.

PVB layer is an important factor for the test as it introduces great changes to the test specimen as there may be PVBs with different thickness. Concentration on PVB layer by means of its material properties is important to reach optimum desired solutions.

Further tests for elongated period of loading may be applied to simulate the effect that may occur on architectural applications.

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